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Extended mixed integer quadratic programming for simultaneous distributed generation location and network reconfiguration

Introduction. *To minimise power loss, maintain the voltage within the acceptable range, and improve power quality in power distribution networks, reconfiguration and optimal distributed generation placement are presented. Power flow analysis and advanced optimization techniques that can handle significant combinatorial problems must be used in distribution network reconfiguration investigations. The optimization approach to be used depends on the size of the distribution network. Our* ***methodology*** *simultaneously addresses two nonlinear discrete optimization problems to construct an intelligent algorithm to identify the best solution. The proposed work is* ***novel*** *in that it the Extended Mixed-Integer Quadratic Programming (EMIQP) technique, a deterministic approach for determining the topology that will effectively minimize power losses in the distribution system by strategically sizing and positioning Distributed Generation (DG) while taking network reconfiguration into account. Using an efficient Quadratic Mixed Integer Programming (QMIP) solver (IBM ®), the resulting optimization problem has a quadratic form. To ascertain the range and impact of various variables, our methodology outperforms cutting-edge algorithms described in the literature in terms of the obtained power loss reduction, according to extensive numerical validation carried out on typical IEEE 33- and 69-bus systems at three different load factors.* ***Practical value****. Examining the effectiveness of concurrent reconfiguration and DG allocation versus sole reconfiguration is done using test cases. According to the findings, network reconfiguration along with the installation of a distributed generator in the proper location, at the proper size, with the proper loss level, and with a higher profile, is effective.* References 24, table 4, figures 14.

Key words: **active distribution networks, distribution system reconfiguration, distributed generation, mixed-integer quadratic programming, power loss.**

Вступ*. Для мінімізації втрат потужності, підтримки напруги в допустимому діапазоні та покращення якості електроенергії у розподільчих мережах представлена реконфігурація та оптимальне розміщення розподіленої генерації. При дослідженнях реконфігурації розподільної мережі необхідно використовувати аналіз потоку потужності та передові методи оптимізації, які можуть вирішувати серйозні комбінаторні проблеми. Підхід до оптимізації, що використовується, залежить від розміру розподільної мережі. Наша* ***методологія*** *одночасно вирішує дві задачі нелінійної дискретної оптимізації, щоби побудувати інтелектуальний алгоритм для визначення найкращого рішення. Пропонована робота є* ***новою****, оскільки вона використовує метод розширеного змішано-цілочисельного квадратичного програмування (EMIQP), детермінований підхід до визначення топології, що ефективно мінімізує втрати потужності в системі розподілу за рахунок стратегічного визначення розмірів та позиціонування розподіленої генерації (DG) з урахуванням реконфігурації мережі. При використанні ефективного солвера Quadratic Mixed Integer Programming (QMIP) (IBM®) результуюча задача оптимізації має квадратичну форму. Щоб з'ясувати діапазон та вплив різних змінних, наша методологія перевершує передові алгоритми, описані в літературі, з точки зору одержаного зниження втрат потужності, згідно з великою числовою перевіркою, проведеною на типових системах з шинами IEEE 33 і 69 при трьох різних коефіцієнтах навантаження.* ***Практична цінність****. Вивчення ефективності одночасної реконфігурації та розподілу DG у порівнянні з єдиною реконфігурацією проводиться з використанням тестових прикладів. Відповідно до результатів, реконфігурація мережі разом із установкою розподіленого генератора в потрібному місці, належного розміру, з належним рівнем втрат і з більш високим профілем є ефективною.* Бібл. 24, табл. 4, рис. 14.

Ключові слова: **активні розподільчі мережі, реконфігурація системи розподілу, розподілена генерація, змішано-цілочисельне квадратичне програмування, втрати потужності.**

Introduction. The last power system supply stage is the electrical distribution network, where the electricity is distributed to individual customers. At the distribution level, the energy could be lost in the form of heat caused by current flow (I^2R). The total power losses of a network could be pretty high for large-scale distribution networks. According to [1] power losses on transmission and sub-transmission lines accounted for 30 % of total power losses, whereas losses in a distribution network may account for 70 % of total power losses. The loss of power directly affects the operating cost of an electrical network. Technically, power losses could also cause a system's voltage profile to change, especially in systems that are heavily loaded.

The power losses in the distribution network can be minimised either by reconfiguring the network or by using (placement and size) multiple distributed generators (DGs). Although these techniques have the capability of loss reduction, their simultaneous combination and implementation will improve the system performance tremendously. Network reconfiguration changes the switches states, which can be normally open (tie switches) or closed (sectionalizing switches). The tie switches are used for the reconfiguration, while the sectionalizing switches isolate the faulted part. These switches help to isolate failed subnets, thus preventing discontinuity and supplying the whole network. The topological structure of the network is changed by closing open switches and vice versa, reducing power losses and improving the overall voltage profile. This will transfer the load to less loaded feeders, which will decrease the overall power loss. Further reductions in power losses can be achieved through the insertion of distributed generation (DG).

DGs are classified into renewable energy resources (RES) and non-RES DGs [2]. On the one hand, some of the RES DGs can only inject active power, such as photovoltaic cells and fuel cells (type P) or inject active and reactive power. Others can inject active power and consume reactive power, such as wind turbines (PQ-type). On the other hand, some non-RES DGs can inject both active and reactive power, such as combined combustion technology (PQ+-type), the internal combustion engine, and combined cycle DGs. Non-RES systems are characterized by the minimization of active and reactive losses, while their main disadvantage is that they have a weak effect on reducing the total cost of production and lead to an increase in global warming [3].

If DG is added to distribution networks in a place that isn't ideal, it will cause more power loss and voltage changes.

Therefore, a strategy for selecting the optimal placement and sizing of the DG must be developed to ensure an optimal configuration. If the distributed generators are correctly installed at optimal locations and if the units are correctly coordinated, they will improve the voltage profile and reduce power losses. The impacts of the reconfiguration and DG allocation techniques are summarized in Table 1 [4].

Table 1

Impacts of reconfiguration, DG allocation techniques

Impacts on techniques	Network reconfiguration	DG allocation
• Voltage support	x	x
• Loss minimization	x	x
• Cost saving		x
• Reliability	x	
• Load balancing		x
THD reduction		
• Demand side management	x	x
• Affects protection system coordination	x	x
• Green energy		x

Several studies use DG placements and network reconfiguration separately to minimise active power losses and improve the voltage profile in distribution networks [5-7]. However, very few offer network reconfiguration to be used in parallel with the location and sizing of DGs for a further reduction in power losses. [8-10].

As more research is done, meta-heuristic, heuristic, hybrid, and analytical techniques for solving functions with one or more objectives are created subject of investigations [11-14].

In [15] proposes a meta-heuristic harmony search algorithm to reconfigure and identify the optimal locations for installing DG units. In [12] presents a new integration technique for optimal network reconfiguration and DG placement. They use the fireworks algorithm, which is a swarm intelligence-based optimization algorithm that is based on how fireworks work to find the best place for the sparks. It is used to reconfigure and assign the best DG units in a distribution network at the same time.

A feeder reconfiguration problem in the presence of distributed generators to minimise the system power loss while satisfying operating constraints using the Hyper Cube-Ant Colony Optimization algorithm has been suggested in [16]. Because the implementation of the Ant Colony Optimization algorithm in the Hyper-Cube framework has the advantage of scaling the value of the objective function, allowing the rapid discovery of reasonable solutions and rapid optimal convergence.

In [17] used the modified plant growth simulation algorithm to minimize the actual power loss. This algorithm does not require barrier factors or crossing rates, as the objectives and constraints are treated separately. From [17], the main advantages of this algorithm are the continuous guided search and the shift target function, as the power of the distributed generation is constantly varying, which can be applied for real-time applications with the necessary modifications. These authors have come up with a way to find the best place to put multiple DGs and the right size for each one to reduce losses and improve voltage profiles.

In [18], a combination of the evolutionary algorithm Strength Pareto Evolutionary Algorithm 2 and the theories of spanning trees are also proposed to optimise several objective functions, providing optimal Pareto solutions, where the network manager can select an option. The results prove that reconfiguring the network with simultaneous placement and sizing of several solar DGs is more beneficial in improving the quality of energy than with a single solar DG. A new technique has been proposed in [19]. A Selective Optimization of Particle Swarms algorithm is used to obtain a reconfigured distribution network and an analytical technique to solve the DG and capacitor placement problem. They proposed a new constant, the power voltage sensitivity constant, for determining the location and size of the candidate bus and a new index, which incorporates the penetration index of the DG and the percentage reduction in actual power losses.

In this work, the Extended Mixed-Integer Quadratic Programming (EMIQP) method minimizes the power losses in a distribution network, including several DG's. EMIQP is applied to simultaneously determine network reconfiguration, DG allocation, and sizing, which can reduce power loss and improve the test profile of the distribution network.

The paper makes a contribution by extending the Taylor formulation [20] to the simultaneously DGs allocation, sizing, and reconfiguration problem.

Three test cases were considered to verify the proposed method, consisting of a distribution network with and without DGs. The results prove the proposed method's ability to produce minimal losses by finding an optimal system topology, DG locations, and adequate sizes.

Problem formulation. Power flow equations. The study of power flow is an essential step in any serious analysis of an electrical network. Indeed, it allows us to calculate the magnitudes of a balanced steady-state network, namely the modules and phases of the voltages at any network point. From these, one can calculate the currents in the lines; the transited active and reactive powers, and the power losses caused during the transport of electrical energy. This analysis is very important for the study, planning, and operation of an electrical network.

The quadratic terms in the DistFlow branch equations represent the losses on the branches; hence, they are much smaller than the branch power terms. The power flow in a radial distribution network can be expressed by a set of recursive equations called distribution flow branch equations (Fig. 1) created by [15]

$$\sum_{k:(i,k)\in E} p_{ik} = p_{ji} - r_{ji}\frac{p_{ji}^2 + q_{ji}^2}{v_j^2} - p_i^L; \qquad (1)$$

$$\sum_{k:(i,k)\in E} q_{ik} = q_{ji} - x_{ij}\frac{p_{ji}^2 + q_{ji}^2}{v_j^2} - p_i^L; \qquad (2)$$

$$v_i^2 = v_j^2 - 2\left(r_{ij} p_{ji} + x_{ij} q_{ji}\right) + \left(r_{ij}^2 + x_{ij}^2\right)\frac{p_{ji}^2 + q_{ji}^2}{v_j^2}; \qquad (3)$$

where p_{ij} and q_{ij} are the active and reactive powers of bus i to bus j; v_i is the voltage magnitude; p_i^L, q_i^L are the real and reactive loads at bus i. Note that p_{ij} and q_{ij} do not equal p_{ji} and q_{ji}. Since v_i does not appear in our formulation, we consider v_i^2 is considered as a variable itself. Let V represent all the buses and E the set of lines, and r_{ij}, x_{ij}, represent the resistance and the reactance of the line, respectively. Single-index constraints represent all (i) in V, and double-index constraints represent all (i, j) in E.

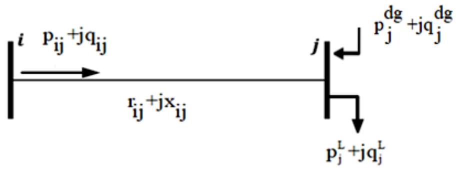

Fig. 1. Simple distribution line

Extended Mixed-Integer Quadratic Programming (EMIQP). The quadratic terms in the equations (1)–(3) represent the line losses which are smaller compared to line power p_{ji} and q_{ji}. Therefore, by removing the second order terms, power flow equations can be simplified [20, 21]. Let E^S be the subset of E with switches, V^F be the subset of V which are substations, p_i^F and q_i^F, $i \in V^F$, be the real and reactive powers from the substations, and M be the sufficiently large disjunctive parameter and α, λ are the aggregate coefficient. Note that the set V^F may contain multiple substations, each of which will be connected to exactly one tree with no other substations attached to it. An EMIQP is obtained for loss minimization by coupling the quadratic objective:

$$\min_{p,q,p^{dg},q^{dg},y,z,h} \sum_{(i,j)} r_{ij}\left(p_{ij}^2 + q_{ij}^2\right) + \alpha \sum_{k=1}^{N_{bus}} \left(p_k^{dg} + q_k^{dg}\right) \ldots + \lambda \sum_{k=1}^{N_{bus}} h_k; \quad (4)$$

And the set of linear constraints:

$$\sum_{j:(i,j)\in E} p_{ji} - p_{ij} = p_i^L, \quad i \in V/V^F; \quad (5)$$

$$\sum_{j:(i,j)\in E} q_{ji} - q_{ij} = q_i^L, \quad i \in V/V^F; \quad (6)$$

$$\sum_{j:(i,j)\in E} p_{ij} = p_i^F, \quad i \in V^F; \quad (7)$$

$$\sum_{j:(i,j)\in E} q_{ij} = q_i^F, \quad i \in V^F. \quad (8)$$

The radiality constraint has represented by two variables z_{ij} and z_{ji} which are assigned to each line indicating which direction, if any, the flow can travel. Each switched line is associated with a single binary variable y_{ij}, which will be equal to zero if the switch is open and equal to one if closed

$$0 \le p_{ij} \le M z_{ij}; \quad (9)$$

$$0 \le q_{ij} \le M z_{ij}; \quad (10)$$

$$z_{ij} \ge 0; \quad (11)$$

$$z_{if} = 0, \quad f \in V^F; \quad (12)$$

$$z_{ij} + z_{ji} = 1, \quad (i,j) \in E/E^S; \quad (13)$$

$$z_{ij} + z_{ji} = y_{ij}, \quad (i,j) \in E^S; \quad (14)$$

$$\sum_{j:(i,j)\in E} z_{ji} = 1, \quad i \in V/V^F; \quad (15)$$

$$y_{ij} \in \{0,1\}, \quad (i,j) \in E^S. \quad (16)$$

Three decision variables are added, p_i^{dg}, q_i^{dg} which are the continuous variables designates the size of the DG's, and h_i is the discrete variable (binary) which designates whether the i^{th} DG is installed or not. It is assumed that the bus where the DG is installed is considered a feeder. Therefore, we have two new constraints (17) and (18), which replace constraints (5) and (6) to simultaneously determine network reconfiguration with siting and sizing of distributed generation (DG)

$$\sum_{j:(i,j)\in V^{DG}} p_{ij} - p_{ji} = h_i \cdot p_i^{dg}, \quad i \in V^{DG}; \quad (17)$$

$$\sum_{j:(i,j)\in V^{DG}} q_{ij} - q_{ji} = h_i \cdot q_i^{dg}, \quad i \in V^{DG}; \quad (18)$$

$$\sum_{i=1}^{N_{dg}} h_i = N_{DG}, \quad i \in V^{DG}. \quad (19)$$

Size of DG units should be within specific limits:

$$\begin{cases} p_{i,\min}^{dg} \le p_i^{dg} \le p_{i,\max}^{dg}; \\ q_{i,\min}^{dg} \le q_i^{dg} \le q_{i,\max}^{dg}; \end{cases} \quad i \in V^{DG}, \quad (20)$$

where $p_{i,\max}^{dg}$, $q_{i,\max}^{dg}$ and $p_{i,\min}^{dg}$, $q_{i,\min}^{dg}$ are the maximum and minimum power supplied by DG, respectively.

The convex optimization problem defined by (4)– (18) is an EMIQP as the objective function (4) is convex quadratic, and the constraint functions are affine [22, 23], but the constraints (17) and (18) are nonlinear; we can replace them by another's linear constraints (21) and (22) using the big M method:

$$\begin{cases} \sum_{j:(i,j)\in E} p_{ij} - p_{ji} \le p_i^{dg}, \quad i \in V^{DG}; \\ p_i^{dg} \le M \cdot h_i; \end{cases} \quad (21)$$

$$\begin{cases} \sum_{j:(i,j)\in E} q_{ij} - q_{ji} \le q_i^{dg}, \quad i \in V^{DG}; \\ q_i^{dg} \le M \cdot h_i; \end{cases} \quad (22)$$

When h_i is equal to one, (21) and (22) are disabled, otherwise p_i^{dg} and q_i^{dg} are set to zero

$$nDG^{\min} \le \sum_{k=1}^{nBus} h_k \le nDG^{\max}, \quad (23)$$

where $nDG^{\min}$, $nDG^{\max}$ are respectively the minimum and the maximum allowed number of DGs. On the grounds that the number DG should be within a specific rang, therefore (23) is added.

In this study, in addition to active power, we are also limiting reactive power because the non-RES DG's (PQ+-type) can inject both active and reactive power. In addition, the radial nature of the distribution network must be maintained, and all loads must be supplied. If one of the above constraints is not respected, the resulting solution will be rejected. Three different scenarios at three different load factors: β = 0.5 (light), β =1.0 (nominal), and β = 1.5 (heavy), are considered to simulate and analyse the performance of the proposed method. These are:

Scenario 1: this base scenario is a power flow solution to the problem.

Scenario 2: this scenario only considers the reconfiguration of the active distribution networks.

Scenario 3: this scenario looks at the reconfiguration of the system as well as the placement and size of three DGs.

Computer simulation and performance analysis studies. The performance analysis of the proposed method was carried out using the two IEEE standard radial distribution system models (IEEE 33-bus and 69-bus) [6], and tolerable results were obtained. The network models of 33 and 69-bus distribution systems, including network reconfiguration, DG allocation, and DG sizing, are implemented in MATLAB. For all these radial systems, the substation voltage was examined as one p.u. The EMIQP models were solved via CPLEX (the CPLEX Optimizer was named for the simplex method implemented in the C programming language) [20, 21]. The numerical computations are carried out on an Intel Core I7-6500U CPU at 2.5 GHz with 8 GB of RAM. Although most of the previous studies focused only on active power injection into the network, the effect of active and reactive power injection of DG units is also considered. The obtained results are verified using other metaheuristics methods.

Case study 1: Using the IEEE 33-Bus Test System. The IEEE 33-Bus System consists of 37 switches, 32 sectionalism switches; and five tie switches. Switch numbers 33, 34, 35, 36, and 37 are normally open for the original network, while the other switches are typically closed, as shown in Fig. 2. The total real load demand is 3715 kW, while the system voltage is 12.66 kV.

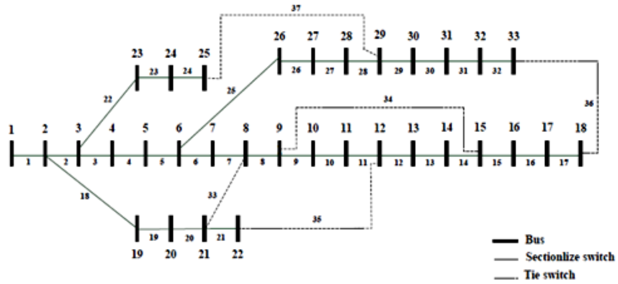

Fig. 2. IEEE 33-bus distribution network before reconfiguration and DG allocation process

The base value of the apparent power is 100 MVA. When the network was first set up, it lost 202.69 kW of power, and the lowest bus voltage was 0.9131 p.u.

The substation (bus 1) voltage is considered as one p.u. All the tie and sectionalising switches are candidate switches for reconfiguration and DG locations. The results obtained from the computer simulation studies are summarised in Table 2. This summary includes the proposed method's performance for three different scenarios, and the results are validated using the metaheuristic algorithms PSO, GWO, and hybrid PSO-GWO [24]. The initial values from the power flow analysis of the 33-bus network are used in Scenario 1.

Table 2

Comparison of simulation results of a 33-bus system

Scenarios		Proposed method (EMIQP)	GWO-PSO [24]	GWO [24]	PSO [24]
Scenario 1	Switches opened	33,34,35,36,37	33,34,35,36,37	33, 34, 35, 36, 37	33, 34, 35, 36, 37
	P loss (kW)	**202.69**	202.67	202.67	202.67
	Q loss (kVAr)	**135.18**	135.14	135.14	135.14
Scenario 2	Switches opened	7,9,14,32,37	7,9,14,32,37	7, 9, 14, 32, 37	7, 9, 14, 32, 37
	P loss (kW)	**139.55**	139.55	139.55	139.55
	Q loss (kVAr)	**102.32**	102.31	102.3	102.3
	Reduction % *P* loss	31.15 %	31.14 %	31.14 %	31.14 %
	Reduction % *Q* loss	24.30 %	24.29 %	24.29 %	24.29 %
	V_{min} (p.u.)	**0.93782**	0.93782	–	–
Scenario 3	Switches opened	06,13,17,21,22	05,11,13,15,23	05, 11, 13, 15, 26	07, 16, 21, 25, 34
	DG size in MVA (bus)	1.075 + j 0.510 (09) 0.930 + j 0.450 (24) 1.010 + j 0.990 (30)	1.0975 + j 0.5593 (08) 1.1523 + j 0.8047 (25) 0.7491 + j 0.5620 (32)	1.0818 + j 0.5138 (8) 1.1327 + j 0.8311 (25) 0.7528 + j 0.5720 (32)	0.7826 + j 0.3752 (12) 0.9533 + j 0.4627 (24) 1.1959 + j 1.0738 (30)
	P loss (kW)	**10.102**	8.916	8.954	10.846
	Q loss (kVAr)	**8.2211**	7.4668	7.53	8.79
	Reduction % *P* loss	**95.01 %**	95.60 %	95.58 %	94.64 %
	Reduction % *Q* loss	**93.92 %**	94.47 %	94.42 %	93.49 %
	V_{min} (p.u.)	**0.9932**	0.97344	–	–
	CPU time (s)	**7,040.3**	12,184.33	26,054.34	23,909.09

From Table 2, it is first observed that the base case power loss of 202.69 kW was reduced to 139.55 kW and 10.102 kW in scenarios 2 and 3, respectively. The percentage reduction in power loss is 31.15 % and 95.01 % in Scenarios 2 and 3, respectively.

Table 2 also shows that the minimum voltage magnitude of the system is improved impressively from 0.9131p.u. up to 0.93782 p.u. and 0.9932 p.u. for scenarios 2 and 3, respectively. It can be seen that the least amount of power is lost in scenario three, where the size and location of the DGs are optimized and the network configuration is optimized.

In this scenario, the real power loss reduction has its lowest value. Figure 3 shows the voltage profile of the 33-bus network. The most flattering voltage profile is achieved in scenario 3, where the minimum voltage magnitude of the network is 0.9131 p.u. and is improved to 0.9378 and 0.9932 for scenarios 2 and 3, respectively. Figure 4 shows the voltage profiles of the network under different case conditions.

These are cases 1 with one DG unit, case 2 with two DG units, and case 3 with three DG units. From this figure, we see that the tension profile of the system is improved for several DGs equal to 3. It can be seen that the integration of several DGs in different places results in a better reduction of the voltage deviation in the distribution network.

Figure 5 indicates active power losses under operating conditions such as Scenario 1, Scenario 2 and 3.

It can be seen that the reduction of the power loss is the highest for scenario three, including PQ+-type DG units.

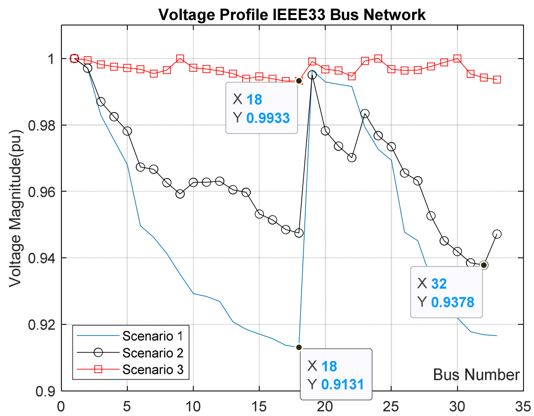

Fig. 3. Bus voltage profile of the networks for 3 scenarios

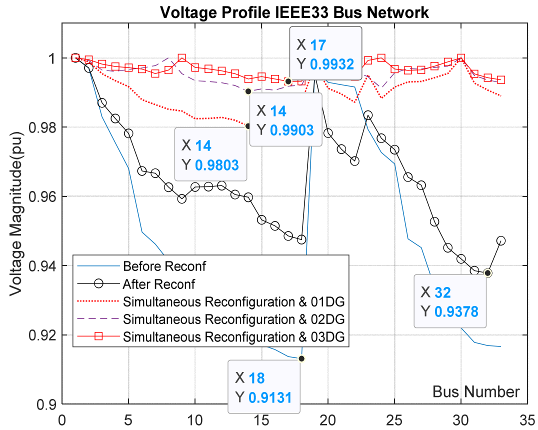

Fig. 4. Bus voltage profile of the 33-bus networks for different network conditions

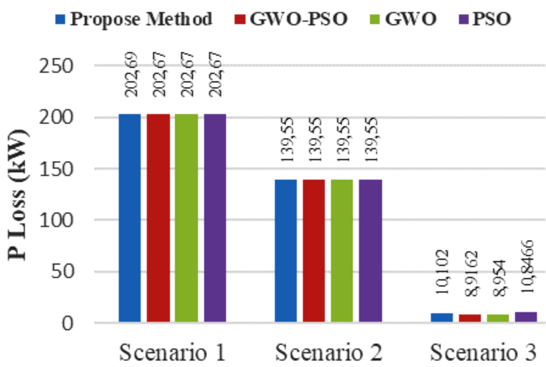

Fig. 5. Power loss of a 33-bus system for 3 different scenarios

From Fig. 6, base case reactive loss is 135.18 kVAr, reduced to 102.32 and 8.2211 for scenarios 2 and 3, respectively, using the proposed technique.

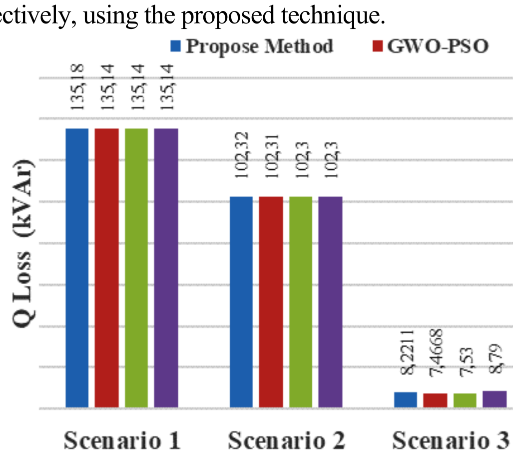

Fig. 6. Reactive loss of a 33-bus system for 3 different scenarios

It has been seen that injecting both active and reactive power at the same time as reconfiguring the system reduces reactive power losses. The proposed technique also improves both the optimal solution and the speed of convergence the most.

Case study 2. Using the IEEE 69-Bus Test System. The 69-bus distribution system includes 69 nodes and 73 branches. There are five tie switches, as shown in Fig. 7. The system load is (3.8 + j2.69) MVA, and the initial active power loss before reconfiguration is 225.04 kW and 102.18 kVAr. The normally open switches are 69, 70, 71, 72, and 73. The system's base capacity is 100 MVA, and the base voltage is 12.66 kV.

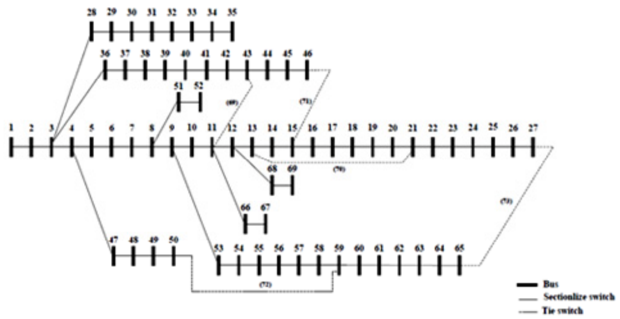

Fig. 7. IEEE 69-bus distribution network before reconfiguration and DG allocation process

Similar to Case Study 1, this case is also simulated for three scenarios, and the results are presented in Table 3. The same observations as in the 33-bus network can be seen regarding the integration of several DGs in multiple locations (Fig. 8), resulting in a better reduction in the power loss and the voltage deviation in the distribution network. From Table 3,the base case power loss is 225.04 kW, reduced to 84.803 and 3.6608 using scenarios 2 and 3, with a percentage reduction of 62.32 % and 98.37 %, respectively, by the integration of DG with PQ+-type and system reconfiguration simultaneously. The minimum voltage magnitude of the network is 0.9131 (p.u.), which is improved to 0.94948 and 0.99588 for scenarios 2 and 3, respectively, using the proposed algorithm. As with the 33-bus test system, the voltage profile of the 69-bus test system for Scenario 3 is seen to be the best (Fig. 9).

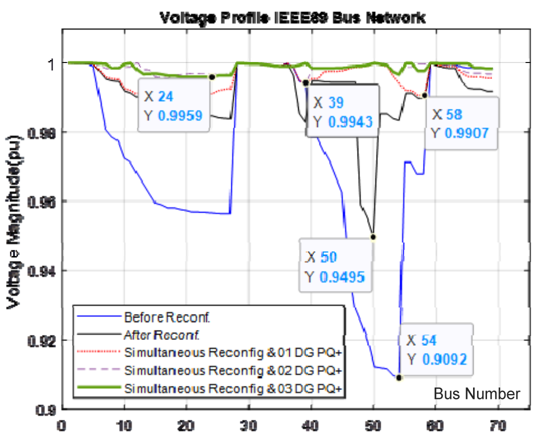

Fig. 8. Bus voltage profiles of the 69-bus network for different network conditions

From Fig. 10, base case active loss is 225.04 kW, which is reduced to 84.803 and 3.6608 using scenarios 2 and 3, respectively, and also, from Fig. 11, base case reactive loss is 102.18 kVAr, which is reduced to 82.623 and 2.1806 using scenarios 2 and 3, respectively.

Table 3
Comparison of simulation results of a 69-bus system

Scenarios		Proposed method (EMIQP)	GWO-PSO [24]	GWO [24]	PSO [24]
Scenario 1	Switches opened	69,70,71,72,73	69,70,71,72,73	69, 70, 71, 72, 73	69, 70, 71, 72, 73
	P loss (kW)	**225.04**	224.93	224.9295	224.9295
	Q loss (kVAr)	**102.18**	102.15	102.14	102.14
Scenario 2	Switches opened	14, 44, 50, 69, 70	14, 57, 61, 69, 70	14, 57, 61, 69, 70	14, 57, 61, 69, 70
	P loss (kW)	**84.803**	98.569	98.5687	98.5687
	Q loss (kVAr)	**82.623**	92.024	92.02	92.02
	Reduction % *P* loss	62.32 %	56.17 %	56.17 %	56.17 %
	Reduction % *Q* loss	19.14 %	9.90 %	9.91 %	9.91 %
	V_{min} (p.u.)	**0.94948**	0.94947	–	–
Scenario 3	Switches opened	07, 13, 18, 24, 35	14, 16, 41, 55, 64	8, 13, 20, 24, 55	12, 21, 40, 53, 70
	DG size in MVA (bus)	1.004 + j 0.697 (11) 0.848 + j 0.605 (39) 1.714 + j 1.224 (50)	0.4319 + j 0.2913 (21) 0.5897 + j 0.4161 (11) 1.6770 + j 1.1979 (61)	0.0887 + j 0.5722 (2) 0.8475 + j 0.5899 (11) 1.7651 + j 1.2605 (61)	1.7298 + j 1.2346 (61) 0.7649 + j 0.5493 (50) 0.7791 + j 0.5339 (43)
	P loss (kW)	**3.6608**	3.7132	5.4798	4.40472
	Q loss (kVAr)	**2.1806**	5.6053	6.54	2.79
	Reduction % *P* loss	98.37 %	98.34 %	97.56 %	98.04 %
	Reduction % *Q* loss	97.87 %	94.51 %	93.59 %	97.26 %
	V_{min} (p.u.)	**0.99588**	0.99486	–	–

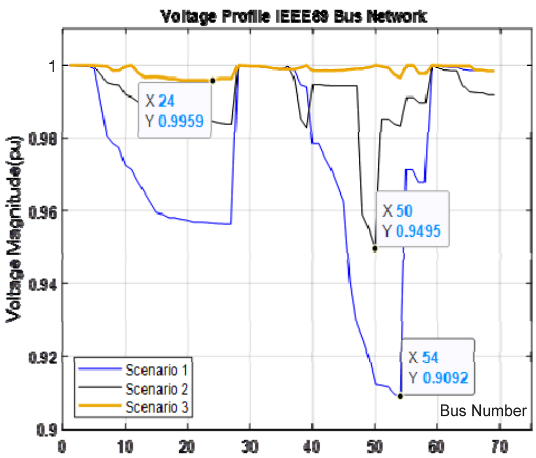

Fig. 9. Bus voltage profiles of the networks for 3 scenarios

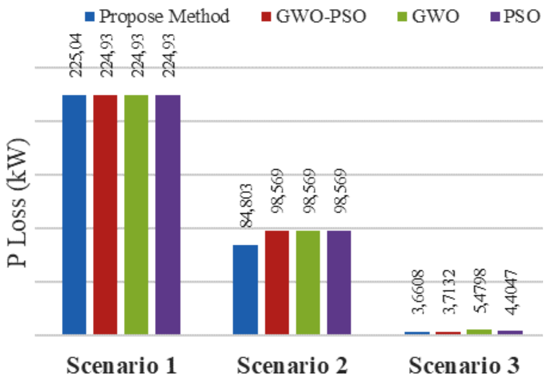

Fig. 10. Power loss of a 69-bus system for 3 different scenarios

Table 3 and Fig. 9 show that the proposed algorithm performs nearly identically to the metaheuristic algorithms PSO, GWO, and hybrid PSO-GWO [24] in terms of solution quality in all scenarios; additionally, the proposed technique offers the best improvement in convergence speed.

Sensitivity analysis. A sensitivity analysis is carried out to determine the range and impact of different variables, and to verify the proposed method's ability to find the optimal solution under different load conditions. Each scenario takes into account three different load factors: light (β = 0,5), nominal (β = 1), and heavy (β = 1,5). Although the heavy load (overload) occurs in emergency conditions.

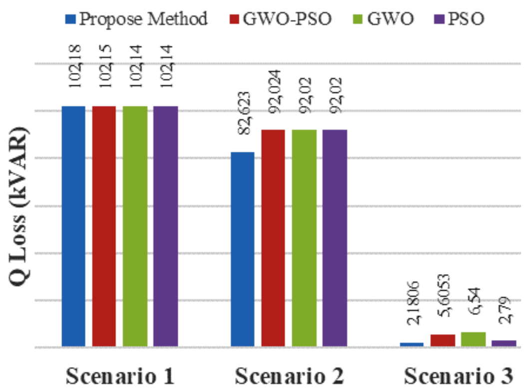

Fig. 11. Reactive loss of a 69-bus system for 3 different scenarios

Table 4 shows that at load factor β = 1.0 (nominal load level), the active power losses in the network with scenario 1 (base case) is 202.69, which is reduced to 139.55 and 10.10 using scenarios 2, and 3, respectively. The percentage reduction in active power losses for scenarios 2 and 3 is 31.15 and 95.02, respectively. Similarly, under load factors β = 0.5 (light) and β = 1.5 (heavy), the percent reduction in active power losses for Scenarios 2 and 3 is 29.32 and 95.37; 33.88 and 95.48, respectively.

It can also be seen from Table 4 that, at all load factors, the magnitude of the minimum voltage of the system is impressively improved in all three scenarios. Under the light, nominal, and high load conditions, the magnitude of the minimum voltage (in p.u.) is improved from 0.9131, 0.9583, and 0.8528 to 0.9968, 0.9932, and 0.9891 in scenarios 1, 2, and 3, respectively (Fig. 12 – Fig. 14).

It is observed that at three load factors, the values of the active and reactive power losses and the minimum voltage are the highest using scenario 3, which proves the superiority of the proposed technique. The improvement in the percentage reduction of active and reactive power losses and the magnitude of the minimum voltage is greater in scenario 3. This shows that changing the network and where the DGs are located at the same time (scenario 3) is better for the quality of the solutions than the other scenarios that were looked at.

Table 4

Performance analysis of proposed method on 33-bus system at different load factors

Scenario	Item	Load level		
		Light (β =0.5)	Nominal (β =1.0)	Heavy (β =1.5)
Base case (scenario I)	Switches opened	33-34-35-36-37	33-34-35-36-37	33-34-35-36-37
	$P_{\mathrm{T,Loss}}$ (kW)	47.072	202.69	575.4
	$Q_{\mathrm{T,Loss}}$ (kVAr)	31.358	135.18	384.37
	V_{min} in p.u.	**0.95826**	**0.91308**	**0.85281**
	(Bus no)	18	18	18
Only reconfiguration (scenario II)	Switches opened	7-9-14-32-37	7-9-14-32-37	7-9-14-32-37
	$P_{\mathrm{T,Loss}}$ (kW)	33.269	139.55	380.45
	$Q_{\mathrm{T,Loss}}$ (kVAr)	24.388	102.32	279.02
	V_{min} in p.u.	**0.96978**	**0.93782**	**0.89667**
	(Bus no)	32	32	32
	% P_{Loss} reduction	**29.32**	**31.15**	**33.88**
Simultaneous reconfiguration and DG installation (scenario III)	Switches opened	5-13-15-20-23	6-13-17-21-22	6-13-17-21-22
	DG size in MW (candidate bus)	0.582 +j 0.277 (8)	1.075 + j 0.510 (09)	1.720 +j 0.816 (9)
		0.540 +j 0.257 (25)	0.930 + j 0.450 (24)	1.488 +j 0.720 (24)
		0.415 +j 0.445 (31)	1.010 + j 0.990 (30)	1.616 +j 1.584 (30)
	$P_{\mathrm{T,Loss}}$ (kW)	2.1795	10.102	26.0004
	$Q_{\mathrm{T,Loss}}$ (kVAr)	1.8406	8.2211	21.166
	V_{in} in p.u.	**0.99684**	**0.9932**	**0.98907**
	(Bus no)	13	17	17
	% P_{Loss} reduction	**95.37**	**95.02**	**95.48**

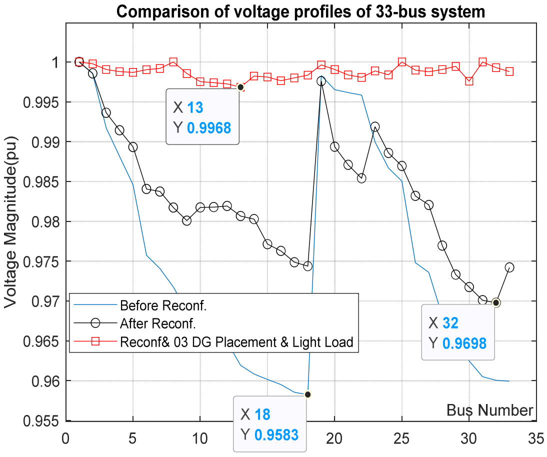

Fig. 12. Comparison of voltage profiles of 33 bus system at light load conditions

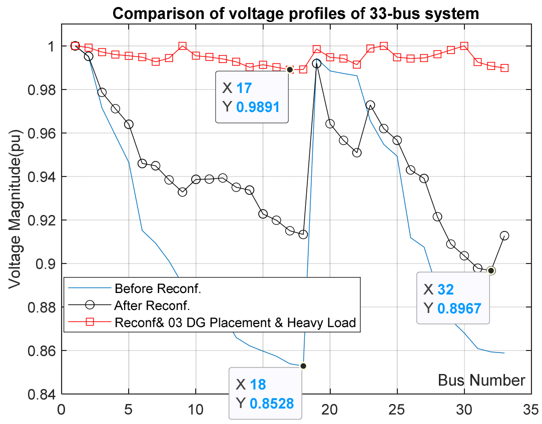

Fig. 13. Comparison of voltage profiles of 33 bus system at nominal load conditions

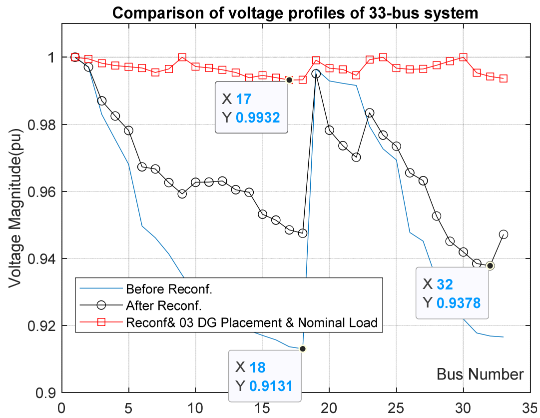

Fig. 14. Comparison of voltage profiles of 33 bus system at heavy load conditions

Conclusions. In this work, an extension of mixed integer quadratic programming (EMIQP) has been successfully applied to the 33 and 69-bus radial systems at different load factors to minimize the power loss, improve the system voltage profile and improve power quality in the active distribution network. Three different scenarios were considered, namely base case, reconfiguration, and simultaneous reconfiguration, with DG's units' location and sizing at three different load factors: β = 0.5 (light), β = 1.0 (nominal), and β = 1.5 (heavy) to analyze the performance of the proposed algorithm. In addition, the proposed method is verified using the metaheuristic algorithms PSO and GWO individually and in a hybrid PSO-GWO. The results indicate that scenario 3 (network reconfiguration with simultaneous DG installation) is more effective in minimising the loss of power and improving the voltage profile compared to the other scenarios considered. Thus, we observe that the proposed algorithm leads to precise results like the other metaheuristic algorithms PSO, GWO, and hybrid PSO-GWO in terms of power losses and voltage profile improvement.

The proposed algorithm outperforms the other metaheuristic algorithms in terms of convergence speed. In addition, this study provides the network manager with a robust tool for technically optimising the distribution network. Future work will be devoted to solving the current optimisation problem for the number of different renewable DG technologies. The goal is to solve this complicated problem by taking into account both the intermittent nature of the power made by renewable DGs and the load.

Conflict of interest. The authors declare no conflict of interest.

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